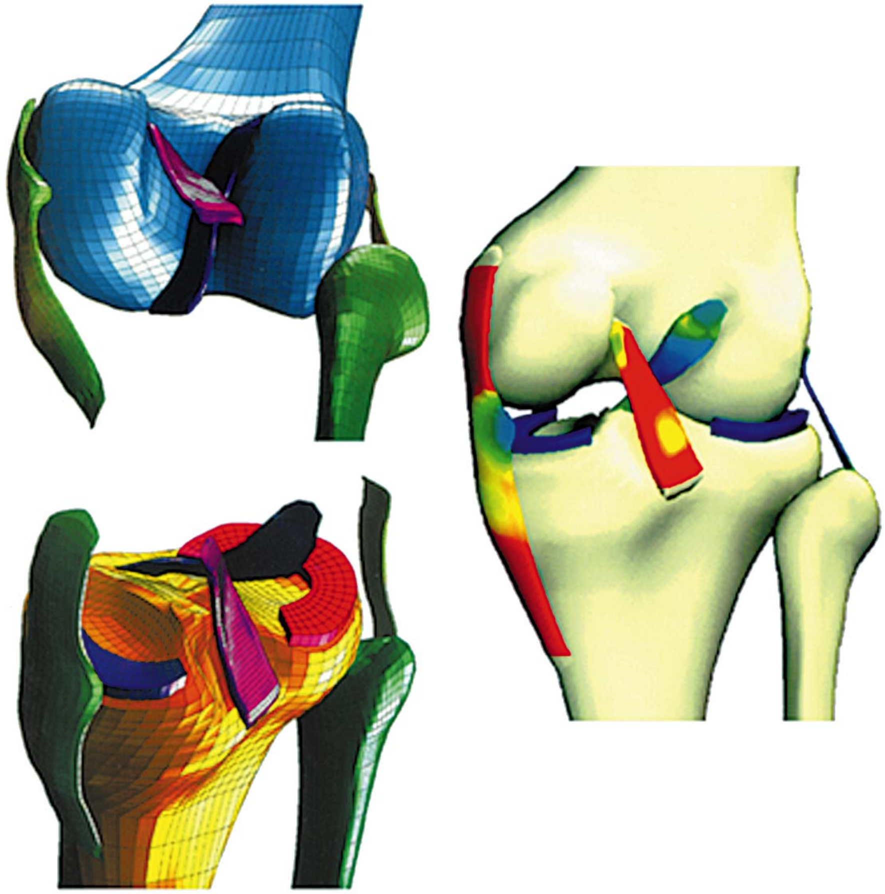
University of California
Lawrence Livermore National Laboratory

Modeling the Biomechanics of Human Joints and Prosthetic Implants



Finite element mesh of knee and simulation of varus-valgus rotation, verifying that the collateral ligaments are the primary restraining structures.

Mission

The Institute for Scientific Computing Research (ISCR) and the Mechanical Engineering (ME) Department at Lawrence Livermore National Laboratory (LLNL) are developing (1) subject-specific computational models of joint anatomy and function and (2) prosthetic joint implant design analyses. Methods developed for these applications can be applied by orthopedists and other physicians as well as academic and industrial researchers to any joint or joint implant.

Impact

Interactive computational orthopedic tools will benefit the clinical treatment and research communities by increasing understanding of natural and prosthetic joint mechanics, the scientific and industrial communities by furthering research in automating the processes for modeling biological materials, and the automobile industry in developing occupant safety features to protect against injury to the lower extremities, head, and chest.

Models of human joint function have traditionally emphasized kinematic data. Some finite element analyses have been applied to prosthetic implants; typically, however, these analyses have been linear and two-dimensional. Nonlinear three-dimensional (3D) finite element models can provide better simulations of bone and soft tissue behavior of joints. These data are difficult to determine experimentally. Our models can help one to understand normal and abnormal joint behavior, such as abnormalities from trauma due to dashboard injuries and microtrauma from repetitive stress.

Objectives

The objective of our collaborative effort is to develop computational models of the dynamics of human joint function, including detailed and subject-specific anatomy; mechanical properties of biological tissues, muscle, and tendon; and human prosthetic joint interactions. We can model specific geometries very accurately starting with image data from computed tomography (CT) or magnetic resonance imaging (MRI). Then we create 3D surface and solid definitions of the object. We are working with radiologists to improve MRI data acquisition to provide high-quality soft tissue differentiation, which is not possible with other imaging modalities at the present time.

Using NIKE3D, we can model bones as homogeneous isotropic materials or as rigid bodies. The soft tissues are anisotropic, inhomogeneous; they undergo large deformation and some exhibit viscoelastic behavior. A transversely isotropic hyperelastic constitutive model was developed to model the fiber-reinforced nature of the ligaments and menisci. Muscles and tendons can be pretensioned to provide joint stabilization. This model better simulates normal soft tissue behaviors under load.

Both of these developments are necessary to enable realistic simula-

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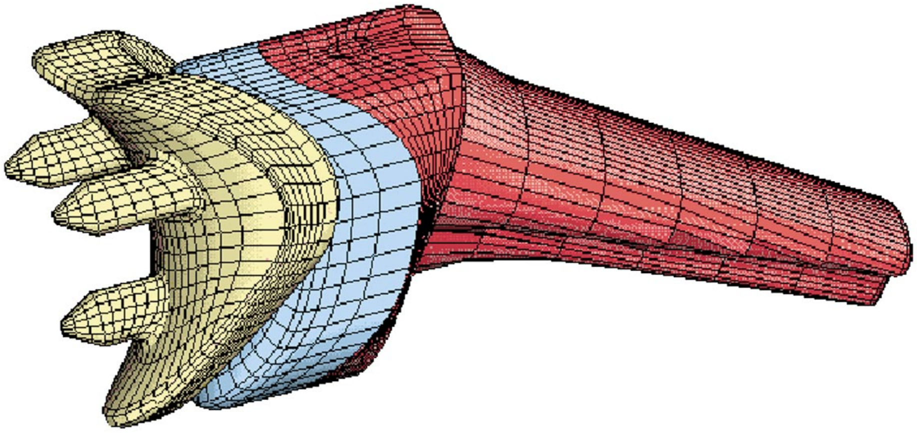

Prosthetic joint implant designs for the thumb carpometacarpal joint. The behavior of each design is modeled with physiological loads applied.

tion of joint mechanics, including both soft tissue and rigid bone structure. We can model the required physical geometry to simulate joint movement, with and without prosthetic implants. Then we can determine the loads in the tissues, assess injury such as from an automobile crash, and animate the resulting motion.

Additional objectives of our research are to develop a human biomechanics database, for rapid access to normal and pathological data. We are also developing automated segmentation tools for image processing and automated techniques that will allow rapid development of high-quality volumetric meshes of biological tissues. To produce an interactive tool appropriate for use in the clinic and the research laboratory, we must demonstrate the capability to produce high-quality modeling results rapidly with minimal human intervention.

Because of their complexity, biological structures represent special problems in running fast code for user interaction and in the development of automated procedures in segmentation, mesh generation, finite element modeling, and visualization. Currently, the computational aspects of this research focus on partitioning the code to run on parallel machines and on automating as much of the modeling process as possible.

Clinical Applications

The computational tools developed here will be broadly applicable in orthopedic treatment and research.

- The models will lead to improved prosthetic joint implant designs, resulting in longer implant life spans and, therefore, fewer costly revision operations.
- The models provide data on internal joint stresses and strains that are not experimentally accessible, to help determine potential mechanisms of injury in repetitive stress and traumatic injuries.
- The models can be used in surgical planning and in assessing the outcome following a traumatic or repetitive motion injury. A surgeon will be able to quantitatively predict outcome measures such as strength, range of motion, and other indicators of functionality.

Future Directions

Our future goals are to:

- Develop new NIKE3D capability to enable more realistic simulation of human tissue behavior.
- Develop noninvasive clinical tools for quantifying the progress of degenerative joint diseases such as osteoarthritis.
- Use the model to determine the predisposition of repetitive strain injuries based on anatomical considerations.
- Evaluate prosthetic joint implant designs for dynamic loads during motion.
- Design partitioning algorithms to optimize parallelization of finite element code for parallel supercomputing machines.
- Design 3D visualization tools for interactively moving tissues to simulate surgical procedures.
- Extend modeling techniques into the area of internal organs such as heart, lungs, and liver.

Our industrial collaborators include XYZ Scientific Applications, Inc., Livermore, California; and ArthroMotion, Warsaw, Indiana. A grant from the Whitaker Foundation and the National Highway Traffic Safety Administration, Biomechanics Division, Washington, DC, are providing funding support for the lower extremity model development. The Utah Supercomputing Institute has provided computer time for simulations.

Our academic and clinical collaborators include:

- Louisiana State University, Shreveport, LA.
- Non-Destructive Evaluation Group, LLNL, Livermore, CA.
- National Highway Traffic Safety Administration, Washington, DC.
- Department of Orthopedic Surgery, University of California at San Francisco.
- Mechanical Engineering Department, University of California at Berkeley.
- Orthopedic Biomechanics Institute, Salt Lake City, UT.
- ExacTech, Inc., Gainsville, FL.

We are actively seeking additional industrial partners to participate in this technology transfer opportunity.

For more information about our project, contact Karin Hollerbach, 510-422-9111, hollerbach1@llnl.gov. or look at: http://www-iscr.llnl.gov and click on the hand icon.

Work performed under the auspices of the U.S. DOE by LLNL under contract No. W-7405-ENG-48